C&O: Finish Ch. 7: Binary Stars. ONLY Cover Sec. 7.1, 7.2
Optional: Sec. 7.3, 7.4 (Radial Velocity, Eclipsing Binaries)

Chapter 8: Sec. 8.1 Spectra 202-211
Sec. 8.1 Optional: 212-219

Sec. 8.2 H-R Diagram

Croswell: Chapters 6-9

**Binary Star Summary**: By measuring: period, distance, inclination, and the size of the (projected) elliptical orbit, we can determine the masses of the two stars:
Spectroscopy

Fraunhofer (1817) observed spectral lines in the Sun.

Henry Draper (1872) took the first photograph of a stars’ spectrum (a spectrogram)

A large program began at Harvard to obtain the spectrum of some 200,000 stars, and classify them using their spectral lines.

Henry Draper (HD) Catalog

People involved:
Edward Pickering, led project
Williamina Fleming, Antonia Maury, Annie Jump Cannon, took data & organized & interpreted it. Came up w/ 7 Spectral Types: O, B, A, F, G, K, M
Spectral Type Definitions

O, B, A F G K M is a temperature sequence: Hot to Cold

**TABLE 8.1** Harvard Spectral Classification.

<table>
<thead>
<tr>
<th>Spectral Type</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>Hottest blue-white stars with few lines</td>
</tr>
<tr>
<td></td>
<td>Strong He II absorption (sometimes emission) lines.</td>
</tr>
<tr>
<td></td>
<td>He I absorption lines becoming stronger.</td>
</tr>
<tr>
<td>B</td>
<td>Hot blue-white</td>
</tr>
<tr>
<td></td>
<td>He I absorption lines strongest at B2.</td>
</tr>
<tr>
<td></td>
<td>H I (Balmer) absorption lines becoming stronger.</td>
</tr>
<tr>
<td>A</td>
<td>White</td>
</tr>
<tr>
<td></td>
<td>Balmer absorption lines strongest at A0, becoming weaker later.</td>
</tr>
<tr>
<td></td>
<td>Ca II absorption lines becoming stronger.</td>
</tr>
<tr>
<td>F</td>
<td>Yellow-white</td>
</tr>
<tr>
<td></td>
<td>Ca II lines continue to strengthen as Balmer lines continue to weaken.</td>
</tr>
<tr>
<td></td>
<td>Neutral metal absorption lines (Fe I, Cr I).</td>
</tr>
</tbody>
</table>
G  Yellow
Solar-type spectra.
Ca II lines continue becoming stronger.
Fe I, other neutral metal lines becoming stronger.

K  Cool orange
Ca II H and K lines strongest at K0, becoming weaker later.
Spectra dominated by metal absorption lines.

M  Cool red
Spectra dominated by molecular absorption bands,
especially titanium oxide (TiO) and vanadium oxide (VO).
Neutral metal absorption lines remain strong.

L  Very cool, dark red
Stronger in infrared than visible.
Strong molecular absorption bands of metal hydrides (CrH, FeH), 
water (H$_2$O), carbon monoxide (CO), and alkali metals (Na, K, Rb, Cs).
TiO and VO are weakening.
Stellar spectra depend sensitively on the TEMPERATURE of the star.
Spectral Lines in a Star Depend on:

• Composition
  (which elements are present?)
  Notation: He II = once ionized Helium, etc

• Ionization State
  (for a given element, how many of its electrons have been stripped off?)

• Quantum Energy Levels
  (for a given ion, which quantized energy levels are populated by electrons?)
How Do We Classify Stars?

- O type stars are the hottest
- M type stars are the coolest.

“Oh, Be A Fine Girl/Guy Kiss Me.”
Spectral Sub-Types

OBAFGKM

- A star’s **spectral type** can be specified more precisely using a **subtype** ranging from 0 to 9.

- Example: spectral type A is divided into A0, A1, A2 .... A9

- A0 is the hottest, and A9 is the coldest.

- F0 is cooler than A9.

- If you know a star’s spectral type, then you know its temperature.

- The Sun is a type G2 star, corresponding to a temperature of 5800 K.
Thermodynamics of Stars

The hotter a gas, the more energy its atoms have, and the higher their velocities.

But not every atom has the same velocity.

The **Boltzmann Distribution** shows the relative number of high $v$ atoms to low $v$.

**Graph:**

- Hydrogen atoms with $T = 10,000$ K
- $v_{mp} = 1.29 \times 10^4$ m s$^{-1}$
- $v_{rms} = 1.57 \times 10^4$ m s$^{-1}$

**Equation:**

- $n_v/n = n_v/n_{max}$
- $n_v/n_{max} = \left(1 + \frac{v^2}{v_{rms}^2}\right)^{-\frac{3}{2}}$

**Diagram Axes:**

- $n_v/n (10^{-5} \text{ s}^{-1})$
- Speed ($10^4$ m s$^{-1}$)
Thermodynamics of Stars

Some of this thermal energy goes into the electrons of each atom, exciting them to different energy states (or ionizing them)

The Saha Equation (Eq. 8.8, optional) gives the fraction of electrons in each energy state.

This determines, eg. whether Hα or H β lines will be seen in the star’s spectrum.

Modern Spectroscopic tools are more complex, and can determine a temperature $T_{\text{eff}}$ for any pattern of spectral lines.
Stars: What do We Know?

- Temperature (T) & Spectral Type
- Distance
- Brightness
  - Luminosity ($L_{\text{star}}$) - energy output of a star
  - Apparent Magnitude (m) - how bright a star appears
  - Absolute Magnitude (M) - how bright a star really is
So many stars... so little time
Organizing the Family of Stars

- To understand the huge diversity of stars, we organize them according to their:
  - Temperature (T)
  - Luminosity ($L_{\text{star}} / L_{\text{Sun}}$)

- How are these properties related?
- To find out, each star is plotted as a point on a graph
  - The x-coord. is Temperature (T)
  - The y-coord. is Luminosity ($L_{\text{star}}$)
Hertzsprung-Russell (HR) Diagram

<table>
<thead>
<tr>
<th>Star</th>
<th>$\frac{L_{\text{STAR}}}{L_{\text{SUN}}}$</th>
<th>Temp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun</td>
<td>1</td>
<td>5800</td>
</tr>
</tbody>
</table>

- Sun: $L_{\text{SUN}} = 1$ (normalized), Temp = 5800 K
- Proxima: $L = 0.002$, Temp = 3000 K
- Vega: $L = 40$, Temp = 10,000 K
- δ Orion: $L = 7000$, Temp = 30,000 K
- Arcturus: $L = 200$, Temp = 4300 K

Main Sequence

Temperature (K)
Henry Norris Russell & Enjar Hertzprung first plotted Abs. Mag. vs. Spectral Type

Russell’s original “H-R Diagram”
Most stars, including the Sun fall on part of the HR Diagram called the Main Sequence.

**Giant Stars** have greater luminosity.

**Supergiants** are even more luminous.

**White Dwarfs** are fainter and bluer.
Stellar radii in the HR diagram
Giant stars can be 100 times the size of the Sun!

If they were in our solar system they would swallow Mercury and Venus!

Supergiant stars are even bigger! 1000 times the size of the Sun!!!
Antares, a SUPERGIANT in Scorpius